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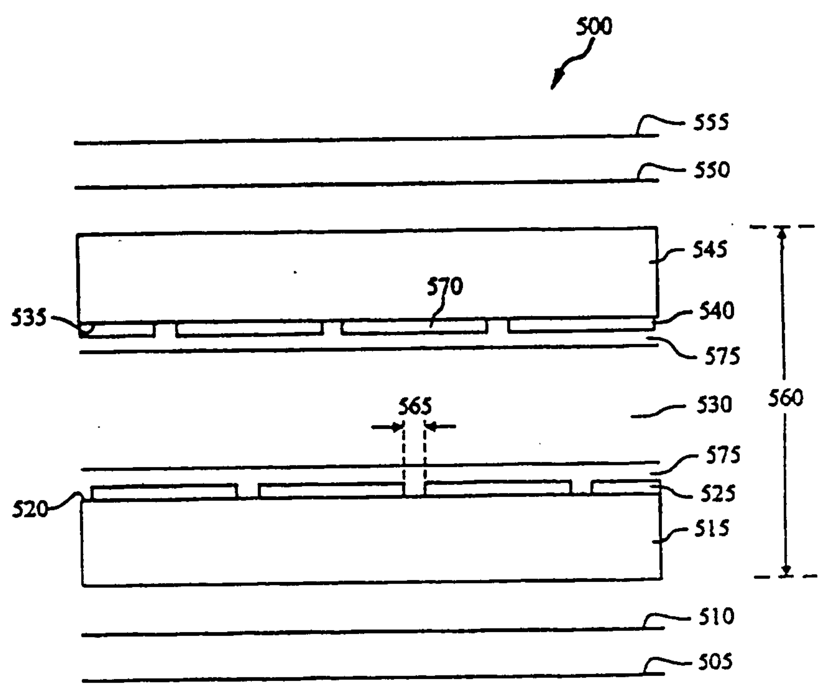
(57) Abstract

A vertically aligned cholesteric liquid crystal display system (500) that provides a high contrast ratio and gray scale transmission that is largely invariant with respect to viewing angle is disclosed. The inventive display consists of an optical compensator and a novel cell design that improves the display's gray scale stability. The display's compensator comprises a negative C-plate (510) and either one or two pairs of crossed A-plates (550). The A-plates are oriented along the display's polarizer transmission axes. The achievable viewing angle using this compensator arrangement is wider than that achievable with crossed polarizers alone. The display's liquid crystal cell design incorporates two tilt domains with a relatively low phase thickness. The liquid crystal's chiral dopant concentration is adjusted to give a cell gap-to-pitch ratio of 0.2 to 0.32. The display's polarizers (505, 555) are oriented at 45° and 135°, whereas the average liquid crystal director is oriented at 90°. Each pixel electrode (525, 540) contains horizontal stripes which produce lateral electric fields within the active pixel region. The lateral electric fields cause the liquid crystal to break up into two tilt domains that are oriented in opposite directions, approximately 90° and 270°. The resulting gray scale response is reproducible from pixel to pixel and relatively uniform with viewing angle because the response from different tilt domains are averaged over the entire pixel. The lateral electric fields also eliminate the instability that exists when an electric potential is first applied across a cell and, thereby, reduces the display's turn-on delay time.



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VIEWING ANGLE ENHANCEMENT FOR VERTICALLY ALIGNED CHOLESTERIC LIQUID CRYSTAL DISPLAYS

BACKGROUND OF THE INVENTION

The invention relates to high information content liquid crystal displays (LCDs) in general, and to vertically aligned cholesteric (VAC) liquid crystal displays in particular. The invention makes use of novel compensation and electrode design for a VAC LCD.

Twisted Nematic Liquid Crystal Displays

Current active matrix liquid crystal display (AMLCD) technology is based almost universally on the 90° twisted nematic (TN) display mode. See Scheffer and Nehring, in "Liquid Crystals Applications and Uses," Vol. 1, B. Bahadur, ed., World Scientific, pp. 231-274, 1990.. This type of display uses a positive dielectric anisotropy ($\Delta\varepsilon = \varepsilon_{\parallel} - \varepsilon_{\perp} > 0$ liquid crystal mixture in which the molecules align with the long axis parallel to the applied electric field. The terms $e_{||}$ and $e_{\perp}$ refer to the low frequency (< 10 kHz) dielectric coefficients parallel and perpendicular, respectively, to the long axis of the liquid crystal molecule.

As shown in Figures 1A and 1B, the inner surfaces of the cell are rubbed to produce alignment (at surfaces **110** and **130**) of the liquid crystal molecules **120** parallel to the surface along the rub direction. The rub directions of the two opposing surfaces **110** and **130** are at right angles to each other. In the undriven or field-off state **100**, the surface anchoring condition (implemented via surface rubbing) forces the liquid crystal molecules **120** to twist 90° from one surface to the other. This causes linearly polarized light propagating from one side of the cell to the other, i.e., toward a viewer **140**, to be rotated 90° nearly independent of wavelength by a mechanism called adiabatic following or "waveguiding". In the normally white (NW) configuration the analyzer **105** and polarizer **135** are perpendicular to each other, causing the undriven state of the NW-TN display to be white. The optical transmission characteristics of the undriven state are largely determined by the phase thickness, *Dnd*, of the liquid crystal cell, where *Dn* is the birefringence of the liquid crystal material **115** and *d* is the cell gap **125**. In one embodiment, optimum transmission and

chromaticity are achieved in the range of 380 nm < *Dnd* < 500 nm.

Application of a transverse electric field above a certain threshold value (known as the Freederickz threshold) causes the liquid crystal molecules **120** to tilt toward a perpendicular alignment, thereby inhibiting the waveguiding effect and producing an elliptical polarization state; see display **145** in Figure 1B. The aforementioned anchoring condition at the surfaces **110** and **130** causes a nonuniform deformation of the liquid crystal molecules **120** from one surface to the other. The NW-TN **145** configuration results in a monotonic decrease in transmission as the applied voltage is increased above the Freederickz threshold voltage.

At a high enough applied voltage, three distinct regions within the cell **145** can be identified. The liquid crystal molecules **120** in the approximately central half of the cell are tilted in a nearly homeotropically alignment (~80°) and experience almost all of the twist. In this region there is little or no rotation of the input light polarization. The liquid crystal molecules **120** in the remaining approximately one-fourth of the cell adjacent to each surface **110** and **130** are aligned along the rub direction. The molecules in these regions experience a moderate amount of tilt but almost no twist. Since the two surface regions are rubbed perpendicular to each other their combined retardation cancels out. At normal incidence, the polarization state of the light propagates nearly unchanged through the cell, giving rise to a contrast ratio of at least 70:1, depending on the drive voltage and extinction ratio of the polarizers **105** and **135**.

In the normally white configuration the fully driven state of the NW-TN display is black at normal incidence. The birefringence of the nearly homeotropic central region causes the transmission of the driven state to increase at off-normal viewing angles. The field of view can be increased somewhat by the use of negative birefringent C-plate optical compensators which effectively cancel out the residual black state birefringence in the central region of the cell. See Ong, "New Normally White Negative Birefringence Film Compensated Twisted Nematic LCDs with Largest

Viewing Angle Performance," Proceedings 12th International Display Research Conference – Japan Display 92, pp. 247-250, 1992.

The normally black configuration, in which the analyzer and polarizer axes are parallel to each other, has also been used to a small extent. The main drawbacks with this configuration, however, are that the peak contrast is not as high, the black state chromaticity is not neutral, and the cell gap tolerance is much tighter than in the NW configuration of Figure 1.

Advantages of the NW-TN configuration include achromatic operation, on-off response times fast enough for video applications, high contrast ratio at normal incidence, and relaxed manufacturing tolerances. Major drawbacks include viewing angle-dependent gray level transmission, relatively slow gray level response times, limited viewing angle, and the need for a mechanical rubbing surface treatment.

Vertically Aligned Nematic Liquid Crystal Displays

Liquid crystal displays have also been demonstrated that operate by an electrically controlled birefringence effect. In particular, the vertically aligned nematic (VAN) display, shown in Figures 2A and 2B, utilizes negative dielectric (*De* < 0) liquid crystal material **210** in which the liquid crystal molecules **215** align perpendicular to an electric field. See Yamauchi et al., ("Homeotropic-Alignment Full-Color LCD," SID 89 Digest, pp. 378-381, 1989) and Hirai et al. ("Optimization of Cell Condition and Driving Method in a VAN LCD for Color Video Display," Proceedings 9th International Display Research Conference – Japan Display '89, pp. 184-187, 1989). It is noted that the VAN type display is also known as a color super homeotropic display.

In the VAN type of display the liquid crystal molecules **215** in the undriven state **200** are homeotropically aligned using a simple application of a surface coupling agent - no rubbing is required. At normal incidence linearly polarized light is largely unaffected as it passes through the liquid crystal material **210**. When the polarizer **105** and analyzer **135** are perpendicular to each other, the linearly polarized light traversing the cell is

absorbed by the analyzer and a normally black display mode is obtained. The contrast ratio of the black state, at normal incidence, is typically greater than 100:1 and is limited only by the extinction ratio of the polarizers and by cell defects. Note, alignment layers **205** and **220** are not subjected to mechanical rubbing operations.

Application of a driving voltage (above the Freederickz threshold, see element **225**) across the liquid crystal cell causes the liquid crystal molecules **215** to tilt toward a parallel alignment. This creates a voltage-dependent birefringence in the liquid crystal material **210** that causes the display to transmit light. Contrary to the NW-TN display, however, the voltage required to reach maximum transmission varies for red, green and blue wavelengths of light. Normally the liquid crystal molecules **215** would tend to tilt in many azimuthal directions, causing multiple tilt domains separated by disclinations. The resulting viewing angle dependence of gray level transmission for a single tilt domain is unacceptably high. Formation of multiple tilt domains within each pixel has been shown to improve the gray scale stability at wide viewing angles. However, the white state transmission of a VAN display depends on the azimuthal direction of the tilt relative to the polarizer transmission axis. The transmission is optimum only if the tilt domains are oriented at nearly 45° relative to the polarizer axes. Randomly oriented tilt domains, and the associated disclinations between them, tend to degrade the VAN's white state transmission.

Patterned electrode designs have been demonstrated that minimize the viewing angle dependence and maximize the white state transmission by stabilizing multiple tilt domains along specific azimuthal directions within each pixel. See Yamauchi et al; Yamamoto et al., ("Full-Cone Wide-Viewing-Angle Multicolor CSH-LCD," SID 91 Digest, pp. 762-765, 1991); and Lien, ("Simulation of Three-Dimensional Director Structures in Multi-Domain Homeotropic LCDs," SID '92 Digest, pp. 33-35, 1992). Nevertheless, the resulting white state transmission is still significantly lower than that typically achieved by a 90° TN display.

In contrast to the NW-TN display, the off-axis transmission in the homeotropically aligned undriven (black) state, which occurs because of the birefringence of the liquid crystal molecules **215**, can be almost completely eliminated by the use of a negative birefringent C-plate compensator. See Yamauchi et al. The result is a display with a black state field of view similar to that of crossed polarizers alone (i.e., without a liquid crystal layer).

VAN displays have both advantages and disadvantages compared to the NW-TN display. Advantages include the avoidance of mechanical rubbing surface treatments and the black state field of view is quite large. Primary drawbacks of the VAN display include low white state transmission levels and the wavelength dependence of the white state transmission level. In a color display, this latter effect requires a different set of drive voltages to be applied to each of the three color sub-pixels. This requirement increases the cost of the driver circuits.

<u>Vertically Aligned Cholesteric Liquid Crystal Displays</u>

The vertically-aligned cholesteric (VAC) display was recently developed to overcome many of the drawbacks of the 90° TN and VAN displays. See Crandall et al., Appl. Phys. Lett., Vol. 65, No. 1, pp. 118-120, 1994.. As in the VAN display, the liquid crystal molecules **310** in the VAC display are homeotropically aligned in the undriven state. In the VAC display, however, the liquid crystal material is doped with a concentration of chiral material sufficient to cause the molecules to twist by approximately 90° in the driven state, that is, when the molecules are oriented nearly parallel to the cell surface. (The VAC display is also known as a homeotropic, rub-free liquid crystal light shutter.)

In the undriven state **300** the homeotropically aligned liquid crystal molecules **310** experience elastic strain, but are constrained not to exhibit twist by the surface anchoring at surfaces **205** and **220**. When a voltage above the Freederickz threshold is applied across the cell (see Figure 3B, element **315**), the liquid crystal molecules **310** begin to tilt toward a parallel alignment. As the molecules begin to tilt away from the surface normal they

begin to twist, thereby relieving the elastic strain. As a result of the twist in the driven state, linearly polarized light is rotated by 90° via the waveguiding effect. In this regard the driven state of the VAC display operates in a manner similar to the undriven state of 90° TN display, even though the surface anchoring condition is different in the two displays. Between the Freederickz threshold and the fully driven state, the cell produces an elliptical polarization state that gives rise to intermediate transmission levels.

The optical transmission characteristics of the VAC's driven state are largely determined by its phase thickness, *Dnd*, and the cell gap-to-liquid crystal pitch ratio, d/P_O, of the liquid crystal cell. Here, *Dn* is the birefringence of the liquid crystal, P_O is the cholesteric pitch, and *d* is the cell gap. For a given value of *Dnd* and d/P_O, the white state voltage is chosen such that the transmission is maximized.

Like the homeotropically aligned VAN display, the VAC display exhibits disclinations between different tilt domains. As long as the tilt domain size is small relative to the dimension of the pixel, a small dependence of the gray scale on viewing angle still exists, but the gray scale transmission is stable over a wider viewing angle than that achieved with a 90° TN display. In the VAC display, the effect of multiple tilt domains on the white state transmission is quite different than in the VAN display however. The white state transmission does not depend on the orientation of the VAC tilt domain. This means that the cell transmission is degraded only by the disclinations themselves, which are generally small relative to the size of the tilt domain itself. Since no disclinations occur in the black state, the black matrix surrounding each pixel can be decreased in width to compensate for any loss in white transmission due to the disclinations.

The size of a typical VAC tilt domain is on the order of 20-70 mm. This is sufficiently small that several tilt domains can exist in the approximately 150 mm x 150 mm pixel sizes typical of current high information content LCDs. Nevertheless, the number of tilt domains is not generally high enough to guarantee that the gray scale transmission will be

symmetrical from opposite viewing directions. Furthermore, the tilt directions are not generally reproducible from pixel-to-pixel, leading to slight differences in off-normal viewing characteristics between adjacent pixels.

The VAC display shares the same advantages over the 90° TN display that the VAN display has, namely that mechanical rubbing surface treatments are avoided and the black state field of view is quite large. In addition to these advantages, the VAC's white state transmission can be made nearly wavelength independent, thereby eliminating the need to drive each pixels three color sub-pixels at different gray scale voltages. Another advantage is that the white state transmission in a multi-domain VAC pixel is higher than in the VAN display.

A drawback to the VAC display, and presumably with VAN displays as well, is that a delay of approximately 30 milliseconds (ms) exists before the liquid crystal molecules begins to tilt after the field is turned. This turn-on delay can be decreased significantly by biasing the off state just below the threshold voltage. Another drawback is that the gray scale transmission becomes nonuniform at viewing angles greater than about 30° from normal. Furthermore, the gray scale transmission at large viewing angles can vary somewhat from pixel-to-pixel (see appendix A).

A well-known significant continuing problem in liquid crystal display technology is that of achieving high contrast and gray scale uniformity over a wide field of view while simultaneously achieving a fast response time for the display of dynamically changing information. The invention addresses these issues in the context of a vertically aligned cholesteric display architecture.

SUMMARY OF THE INVENTION

The vertically aligned cholesteric (VAC) liquid crystal display (LCD) system in accordance with the invention provides a high contrast ratio and gray scale transmission that is largely invariant with respect to viewing angle. Specifically, the inventive display consists of an optical compensator for improving the contrast ratio and a novel cell design that improves the display's gray scale stability.

A simple and effective liquid crystal display compensator in accordance with the invention is comprised of a negative C-plate and a positive A-plate. The C-plate is disposed between the light entrance polarizer and the liquid crystal cell, the A-plate is disposed between the liquid crystal cell and the exit polarizer (analyzer). The A-plate is oriented with its optic axis nearly parallel to the transmission axis of the analyzer. Using this compensator, the range of viewing angles over which black state transmission remains very low is much wider than that with crossed polarizers alone. Alternatively, one or more pairs of crossed A-plates can be used instead of a single A-plate and additional negative birefringent C-plates can also be used.

The display's pixel design incorporates either two or four liquid crystal tilt domains with a relatively low phase thickness of 300 to 450 nanometer (nm). The liquid crystal's chiral dopant concentration is adjusted to give a cell gap-to-pitch ratio of 0.2 to 0.32. The display's polarizers are oriented at 45° and 135°. To achieve a two tilt domain pixel, each pixel electrode is patterned into parallel stripes which produce lateral electric fields in the driven state within the active pixel region. The lateral electric fields cause the liquid crystal molecules to separate into two tilt domains that are oriented in substantially opposite directions; approximately 90° and 270°. To achieve a four tilt domain pixel, each pixel electrode contains rectangular holes which produce lateral electric fields within the active pixel region. The lateral electric fields cause the liquid crystal molecules to separate into four tilt

domains that are oriented in four directions separated by approximately 90°; that is, approximately 0°, 90°, 180°, and 270°.

The resulting gray scale response is reproducible from pixel to pixel and relatively uniform with viewing angle because the responses from different tilt domains are averaged over the entire pixel. The lateral electric fields reduce the slope of the electro-optic curve. Lateral electric fields also eliminate the instability that exists when an electric potential is first applied across a cell and, thereby, reduce the display's turn-on delay time.

BRIEF DESCRIPTION OF DRAWINGS

Figures 1A and 1B are cross sectional views of a conventional normally white, 90° twisted nematic liquid crystal display (undriven and driven states respectively).

Figures 2A and 2B are cross sectional views of a conventional normally black, vertically aligned nematic liquid crystal display (undriven and driven states respectively).

Figures 3A and 3B are cross sectional views of a conventional normally black, vertically aligned cholesteric liquid crystal display (undriven and driven states respectively).

Figure 4 depicts a coordinate system used to specify component orientations within the instant invention.

Figure 5 shows a cross sectional view of a vertically aligned cholesteric display cell in accordance with the invention.

Figure 6 shows, in plan view, an expanded view of the electrode structure of Figure 5.

Figure 7 shows an expanded cross sectional view of the liquid crystal display cell of Figure 5.

DETAILED DESCRIPTION OF A SPECIFIC EMBODIMENT

An illustrative embodiment of the invention is described below as it might be implemented using liquid crystal display techniques. In the interest of clarity, not all features of an actual implementation are described in this specification. It will of course be appreciated that in the development of any such actual implementation (as in any development project), numerous implementation-specific decisions must be made to achieve the developers' specific goals and subgoals, such as compliance with system- and business-related constraints, which will vary from one implementation to another. Moreover, it will be appreciated that such a development effort might be complex and time-consuming, but would nevertheless be a routine undertaking of device engineering for those of ordinary skill having the benefit of this disclosure.

For the benefit of the reader, additional detailed technical information relating to a preliminary engineering analysis for one embodiment of the inventive display may be found in Appendix A, entitled "Preliminary Evaluation of VAC Optical Performance." (Appendix A is a copy of a technical memorandum submitted by one of the inventors and is included, without its originally accompanying drawings, as supplemental disclosure.)

Figure 4 depicts the coordinate system used herein to describe the orientation of both liquid crystal and birefringent compensator optic axes. Light propagates toward the viewer **400** in the positive z direction **405** which, together with the x-axis **410** and the y-axis **415**, form a right-handed coordinate system. Backlighting is provided, as indicated by the arrows **420**, from the negative z direction. The polar tilt angle Θ **425** is defined as the angle between the molecular optic axis $\hat{c}$ **430** and the x-y plane, measured from the x-y plane. The azimuthal or twist angle Φ **435** is measured from the x-axis **410** to the projection **440** of the optic axis **430** into the x-y plane.

Structure Of A Specific Embodiment

Figure 5 shows a region within a single addressable picture element of

a liquid crystal display **500** that includes a polarizer **505**, a compensator layer **510**, a first substrate **515** having on its surface **520** a first segmented electrode **525**, a liquid crystal layer **530**, a second segmented electrode **540** on a surface **535** of a substrate **545**, a second compensator layer **550**, and an analyzer **555**. The areas between and including the substrates **515** and **545** are referred to as a liquid crystal cell **560**; the physical thickness of the liquid crystal layer **530** is commonly referred to as the cell gap *d* of the cell.

The liquid crystal layer **530** is composed of a liquid crystal material that has a negative dielectric anisotropy. The liquid crystal material sold by the Merck company under designation Merck ZLI-2787 has been found to be satisfactory in preliminary tests. The above-referenced Merck liquid crystal material has a negative dielectric anisotropy ($\Delta\varepsilon$) of -3.5, an elastic constant ratio ($K_{33} \div K_{11}$) of 1.25, a birefringence of 0.074, and contains a concentration of chiral dopant sufficient to give a cell gap-to-pitch ratio of -0.22 (left-handed pitch).

As shown in plan view in Figure 6, the electrodes **525** and **540** may be composed of a pattern of horizontal indium-tin oxide (ITO) stripes **600**. Each stripe is approximately 43 micrometers (μm) wide, with two adjacent stripes being separated by an approximately 7 μm gap **565**. The striping is repeated essentially continuously over the surfaces **520** and **535** of the substrates **515** and **545** in each pixel.

Alternatively, a different pattern can be employed to produce a larger number of stable tilt domains. In preliminary modeling it has been found that four tilt domains are particularly beneficial. The azimuthal direction of the tilt domains may be oriented at approximately 0°, 90°, 180° and 270°. The relative area of each domain need not be the same. For instance, the area of the 90° and 270° oriented domains may be approximately twice that of the 0° and 180° domains. This arrangement appears to produce more symmetric viewing angle characteristics (e.g., contrast and gray scale stability) because of the averaging of the viewing angle response over the four different domains within each pixel.

Referring again to Figure 5, the first electrode **525** is aligned with respect to the second electrode **540** such that the gaps **565** on the first electrode **525** are centered below the ITO regions **570** of the electrode **540**. The substrates **515** and **545** further have an alignment layer **575** that covers the entire surface of the substrate, including the electrodes **525** and **540**. The alignment layer **575** produces a homeotropic (vertical) alignment of the liquid crystal molecules in the undriven state. The alignment layer may be composed of lecithin, long alkyl-chain silanes, long alkyl-chain carboxylato-chromium complexes, polymers, or other materials as well known to those of ordinary skill.

The liquid crystal cell may have a thickness of approximately 5.0 µm, producing a phase retardation for the liquid crystal cell (Δnd) of approximately 370 nm. The compensator layer **510** may consist of a negative C-plate layer with a phase retardation of approximately 290 nm. The compensator layer **550** may consist of a positive A-plate with a phase retardation of approximately 130 nm. The azimuthal orientation of the A-plate layer is such that its optic axis is nearly parallel to the transmission axis of the adjacent analyzer layer **555**.

Alternatively, one or more pairs of crossed A-plates, placed at any convenient location between the polarizer **505** and the anlayzer **555**, may be used instead of the compensator layer **550**. Additional negatively birefringent C-plates may also be used in the embodiment of Figure 5.

The polarizer **505** and the analyzer **555** have their respective absorbing axes oriented perpendicular to each other (in a normally black display). In one embodiment, the absorbing axes are oriented at approximately a 45° angle to the stripes **600**.

<u>Operation</u>

The use of an elastic constant ratio ($K_{33} \div K_{11}$) of less than approximately 1.5, a cell gap-to-pitch ratio (d/P_0) of between 0.2 and 0.3, and a liquid crystal phase retardation (Δnd) of between 300 nm and 500 nm reduces the slope of the electro-optic curve at drive voltages above the

Freederickz threshold, while still maintaining a high transmission in the fully driven state. The lower slope improves the stability of gray scale transmission over a wide field of view.

Referring to Figure 7, when an electric field is applied across the liquid crystal layer **530** by application of a voltage across the electrodes **525** and **540**, the liquid crystal molecules in the center of the layer **530** tilt toward a parallel orientation with respect to the surfaces **520** and **535** of the substrates **515** and **545**. The gaps **565** in the electrodes **525** and **540** create lateral components of the electric field that induce the liquid crystal molecules in the regions labeled **700** to tilt in a left-handed direction, whereas the liquid crystal molecules in the regions labeled **705** tilt in a right-handed direction. Furthermore, the lateral electric field component reduces the Freederickz threshold voltage which reduces the slope of the average electro-optic curve.

The gray scale transmission characteristics of a single liquid crystal region **700** or **705** are strongly dependent on the viewing angle. A noteworthy benefit of the instant invention is that the transmission characteristics of the region **700** in the liquid crystal layer **530** are averaged, from the viewer's perspective, with those of the region **705**. The average gray level transmission characteristics of the two regions **700** and **705** exhibit improved stability over a wide field of view.

The negative C-plate **510** compensates for the positive C-plate optical characteristics of the liquid crystal material **530** when in the undriven state. The A-plate **550** compensates for the intrinsic leakage in the transmission properties of crossed polarizes at wide viewing angles. The combined effect of both compensators, **510** and **550** is to significantly reduce the transmission of the black (undriven) state of the display over a wide field of view.

<u>Benefits</u>

There are at least Four major performance benefits of a VAC display in accordance with the invention. First, the viewing angle with negative C-plate and positive A-plate compensation is expected to be wider than previously available in other LCD systems. This makes possible the use of

such displays in advanced avionics systems as well as any other information display location. Second, the existence of multiple tilt domains within the liquid crystal material means that, on the average, the gray level transmission is fairly insensitive to viewing angle and is the same from one pixel to another. Third, the turn-on delay time is reduced by the use of lateral electric fields within the transmitting pixel region. Finally, the rubless alignment process can result in high production yields.

It will be appreciated by those of ordinary skill having the benefit of this disclosure that numerous variations from the foregoing illustration will be possible without departing from the inventive concept described herein. Accordingly, it is the claims set forth below, and not merely the foregoing illustration, which are intended to define the exclusive rights claimed in this application program.

APPENDIX A: PRELIMINARY EVALUATION OF VAC OPTICAL PERFORMANCE

Rockwell Science Center performed a preliminary experimental and theoretical evaluation of the vertically aligned cholesteric (VAC) liquid crystal display to determine its suitability for high information content display applications. Our evaluation was based on modeling and experimental measurements on test cells fabricated at Case Western Reserve University (CWRU) and Science Center. We conclude that the VAC architecture is a promising display technology for commercial avionics systems as well as other information display applications. We also identify several deficiencies with the current VAC cell design and recommend technical areas that require further investigation. This document discloses results of work done at Science Center during this evaluation.

Modeling Accuracy

Our model results were qualitatively confirmed by our experimental measurements. We calculated the liquid crystal deformation profile using the DIMOS modeling software from Autronic-Melchers. Rigid boundary conditions were used for both azimuthal and polar anchoring on the input substrate as well as for the polar anchoring on the output substrate, and elastic boundary conditions were used for the azimuthal anchoring on the output substrate. All material parameters necessary for modeling were available for the liquid crystal mixture Merck ZLI-2787. All parameters but the K_{33}/K_{22} elastic ratio were known for the liquid crystal mixture Merck MLC-2011. A reasonable estimate can often be made of the K_{33}/K_{22} ratio, however, since K_{22} is usually 0.5-0.6 times K_{11}.

The optical properties of VAC liquid crystal cells were modeled using the extended 2x2 Jones matrix algorithm [1]. The optical performance of a test cell with random tilt domains was simulated by averaging over 12 liquid crystal orientations, each orientation being rotated by 15° relative to the previous one.

The optical effect of disclinations was not included in our model.

The black state transmission of the VAC test cell from CWRU deteriorated over the course of our measurements, so we fabricated two test cells using ZLI-2787 with 5 and 10 mm cell gaps. Good quantitative agreement between modeling and measurement was obtained for the contrast ratio conoscopes. Poor quantitative agreement was obtained for transmission versus polar viewing angle, presumably due to a non-random orientation of the tilt domains in the test cells.

Field of View

Our modeling and measurements confirm our expectation that the use of negative c-plate compensation can improve the VAC viewing angle. The viewing angle is unaffected by the azimuthal orientation of the liquid crystal in the driven state. The peak contrast ratio is limited only by the polarizer efficiency, color filters, and defects in the cell resulting from cell spacers and surface topology.

Grayscale Linearity

Poor grayscale linearity was observed in the modeled and measured results for VAC test cells. This problem was studied by modeling the transmission versus polar viewing angle for a single tilt domain. A severe rebound develops at 20-30° in either the horizontal or vertical viewing direction, depending on the liquid crystal azimuthal orientation relative to the polarizers. The orthogonal viewing direction has good grayscale linearity, however. In the case of a test cell, which presumably has randomly oriented tilt domains, a smaller but nevertheless objectionable rebound occurs in all viewing directions.

As indicated above, the grayscale performance of the test cell was not the same for horizontal and vertical directions (parallel to the polarizer axes), indicating that the domains were not randomly oriented in the area being measured. We expect this to be the case in a pixel as well because lateral fields resulting from the electrode boundaries will tend to induce specific

azimuthal tilt directions. We found that good grayscale performance could still be obtained, however, by using two tilt domains having their average liquid crystal director oriented in the vertical plane but in opposite directions. The polarizers were oriented at 45 and 135°, rather than at 0 and 90°. This type of tilt orientation can be created, for example, by the use of narrow slits in the pixel electrodes, appropriately oriented to induce lateral electric fields in the vertical direction. The use of lateral electric fields within the pixel may also overcome the problem of turn-on delay. Up to four tilt domains are also feasible with structured electrodes, which may further improve the grayscale linearity.

The grayscale performance was studied in some detail and a crude optimization of the liquid crystal parameters and cell thickness was performed with the goal improving the grayscale linearity. The results reveal a strong dependence of the rebound on the cell phase thickness, Dnd. Decreasing the phase thickness improves the grayscale linearity, but also decreases the cell transmission in the white state. To a much lesser degree, the rebound increases with increasing elastic constant ratio, K_{33}/K_{11}, and decreasing dielectric anisotropy ratio, $De/e_{||}$. The only way to recover the white state transmission is by increasing the pitch, or conversely, decreasing cell gap-to-pitch ratio, d/p. We were able to obtain good grayscale linearity from a two-domain cell by using a phase thickness of Dnd=340 nm, a domain area ratio of 65/35, and a d/p ratio of -0.22. Further improvement in the performance may be necessary, however, to achieve full compliance with avionics grayscale specifications.

The white state transmission for this configuration was about 15% lower than that for a normally white 90° TN cell. The lower transmission can possibly be compensated by increasing the aperture ratio (disclinations at the pixel boundaries do not adversely effect black state transmission, because the VAC uses a normally black polarizer configuration), and/or changing the backlight

phosphor mix (see below).

Chromaticity

As mentioned above, the chromaticity of a VAC display configured for optimum grayscale linearity (low Dnd) has a relatively high blue transmission. This characteristic may improve overall system efficiency because the backlight needs less blue phosphor, which is less efficient than the green phosphor. Furthermore, the shape of the electro-optic curve appears to be nearly the same for red, green and blue. The gray level chromaticity is most stable at high viewing angles and least stable at normal incidence. The effect on chromaticity of the red, green and blue pixels having different cell gaps may improve the chromaticity but was not specifically investigated.

VAC Development Issues

Several technical issues were identified from our evaluation that require further development. These issues are described below, along with suggested technical approaches.

Multi-Domain Electrode Design. The electrode pattern must be optimized to produce stable orientation of the tilt domains over a wide temperature range. The feasibility of this approach for vertically aligned nematic (VAN) displays has already been demonstrated [2-4].

Grayscale Response Time. Preliminary results suggest response times of up to 200 ms for some transitions between gray levels (CWRU test cell). The effect of d/p ratio and other liquid crystal material parameters on the response time must be determined. This issue can be investigated theoretically using DIMOS. Multiple-pulse electronic drive schemes may be needed to achieve response times short enough for video applications. Some experimental measurements must be performed to validate the modeling results. This plan for this work will depend somewhat on range of mixture parameters available from commercial liquid crystal materials.

Furthermore, the use of lateral electric fields should reduce the turn-on

delay time observed in the early VAC test cells. This prediction must be confirmed with test cell measurements.

Optimized Cell Design / Liquid Crystal Mixture Parameters. The goal is good grayscale linearity and chromaticity stability over a +/- 60° horizontal and +/- 45° field of view, as well as >100:1 contrast ratio over +/- 60 in all directions. Any proposed modification to the cell architecture must be thoroughly evaluated theoretically to determine the effect on grayscale and chromaticity stability, and response time.

Homeotropic Alignment Layer. Good alignment was demonstrated with a siloxane surfactant, although some surface defects were observed. Other potential alignment materials, such as polymers and other surfactants, must be evaluated over a wide temperature range for alignment stability and voltage holding ratio. If high purity materials are not available, then it may be possible to use surface cleaning procedures to improve the voltage holding ratio of surfaces treated with relatively impure alignment materials.

Liquid Crystal Mixture. All of the two-domain modeling was done with parameters for Merck MLC-2011. The clearing point of this mixture is only 73 °C, which is at least 20°C below that required for avionics applications. Alternative materials must be identified and evaluated.

References

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2. S. Yamauchi, M. Aizawa, J.F. Clerc, T. Uchida, and J. Duchene, SID '89 Digest of Technical Papers, p. 378 (1989).
3. T. Yamamoto, S. Hirose, J.F. Clerc, Y. Kondo, S. Yamauchi, and M. Aizawa, SID '91 Digest of Technical Papers, p. 672 (1991).
4. A. Lien, SID '92 Digest, p. 33 (1992).

CLAIMS

WHAT IS CLAIMED IS:

1. A liquid crystal cell for a liquid crystal display, said liquid crystal cell comprising:
   (a) a liquid crystal layer defined by a plurality of layer surfaces:
      (1) said liquid crystal layer having (A) a negative dielectric anisotropy, (B) a K_{33}/K_{11} elastic constant ratio less than about 1.5, (C) a phase retardation of between about 300 nanometers and about 550 nanometers;
      (2) said liquid crystal layer comprising a plurality of liquid crystal molecules, wherein said liquid crystal molecules that are adjacent to said layer surfaces are aligned homeotropically, and
      (3) said liquid crystal layer further comprising a chiral dopant of sufficient concentration to achieve a cell-gap-to-pitch ratio of between approximately 0.2 to approximately 0.35;
      (4) said liquid crystal molecules being organized in a plurality of tilt domains;
   (b) a first electrode proximate to a first major surface of the liquid crystal layer;
   (c) a second electrode proximate to a second major surface of the liquid crystal layer, the first and second electrodes being adapted to apply an electric field across the liquid crystal layer when the electrodes are connected to a source of electrical potential; and
   (d) either or both of said first electrode and said second electrode including a plurality of discontinuities producing one or more lateral components to said electric field, each of said one or more lateral components defining an azimuthal direction for at least one of said tilt domains.

2. A liquid crystal cell for a liquid crystal display, said liquid crystal cell comprising:
   (a) a liquid crystal layer defined by a plurality of layer surfaces and having a negative dielectric anisotropy, said liquid crystal layer comprising:
      (1) a plurality of liquid crystal molecules that are organized in a plurality of tilt domains, said liquid crystal molecules that are adjacent to said layer surfaces being aligned substantially homeotropically, and
      (2) a chiral dopant of sufficient concentration to achieve a cell-gap-to-pitch ratio of between approximately 0.2 to approximately 0.35;
   (b) a first electrode proximate to a first major surface of the liquid crystal layer; and
   (c) a second electrode proximate to a second major surface of the liquid crystal layer, the first and second electrodes being adapted to apply a voltage across the liquid crystal layer when the electrodes are connected to a source of electrical potential.

3. The liquid crystal cell of claim 2, wherein either or both of said first electrode and said second electrode include one or more discontinuities producing one or more lateral components to said electric field.

4. The liquid crystal cell of claim 3, wherein an azimuthal direction of said tilt domains is defined by said lateral component to said electric field.

5. The liquid crystal cell of either of claims 3 or 4, wherein said liquid crystal molecules that are adjacent to said layer surfaces are aligned homeotropically.

6. The liquid crystal cell of claim 2, wherein a phase retardation of said liquid crystal layer is between about 300 nanometers and about 550 nanometers.

7. The liquid crystal cell of claim 2, wherein said liquid crystal display is a normally black display.

8. The liquid crystal cell of claim 2, wherein a K_{33}/K_{11} elastic constant ratio of said liquid crystal layer is less than about 1.5.

9. A liquid crystal display comprising:
   (a) a polarizer layer;
   (b) an analyzer layer;
   (c) a liquid crystal cell in accordance with a specified one of claims 1, 2, 3, 4, 5, 6, 7, or 8 and
   (d) at least one compensator layer disposed between said polarizer and said analyzer and comprising at least one negatively birefringent C-plate layer.

10. The display of claim 9, wherein said compensator layer further comprises at least one positively birefringent A-plate layer.

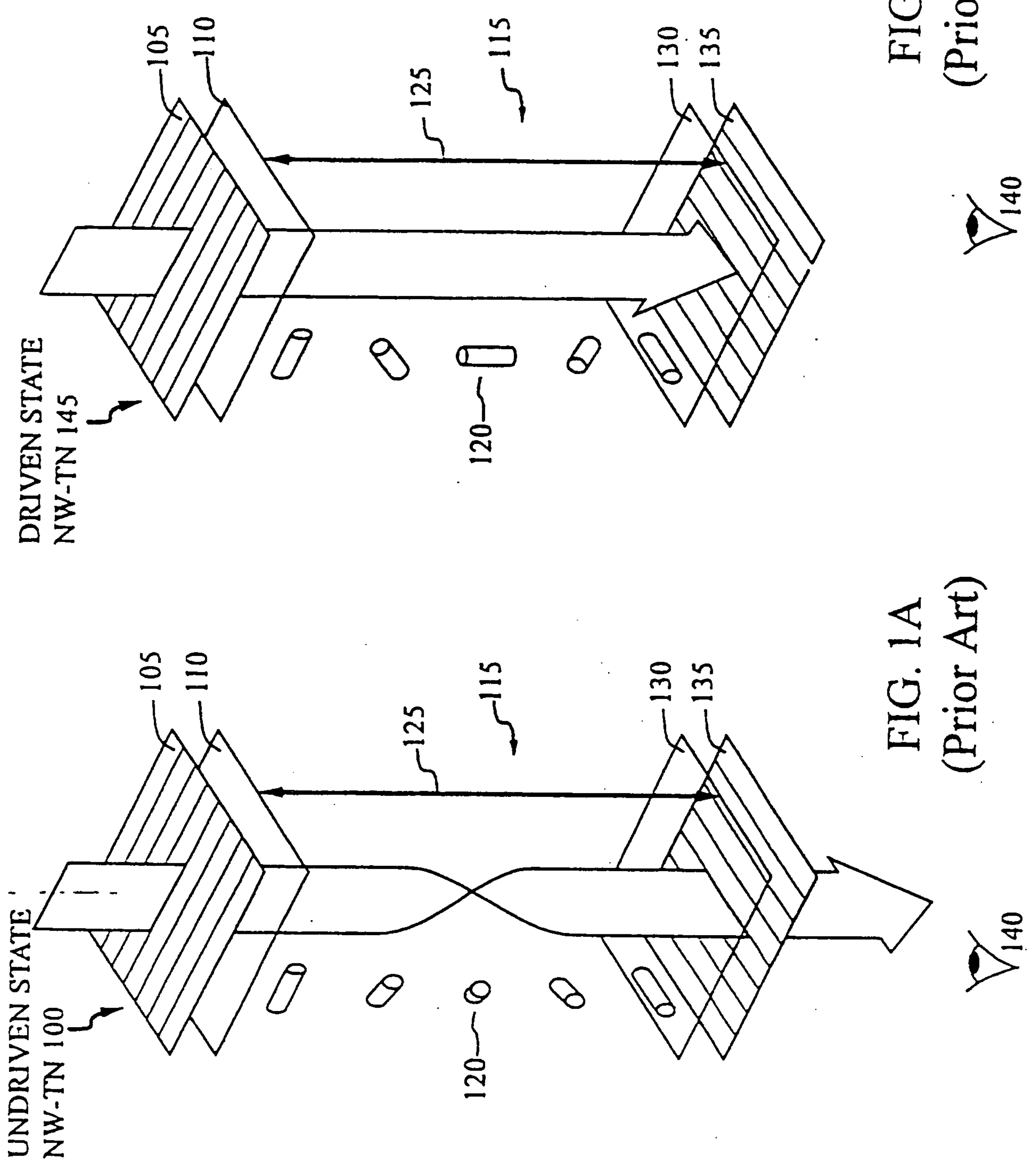

FIG. 1B
(Prior Art)

FIG. 1A
(Prior Art)

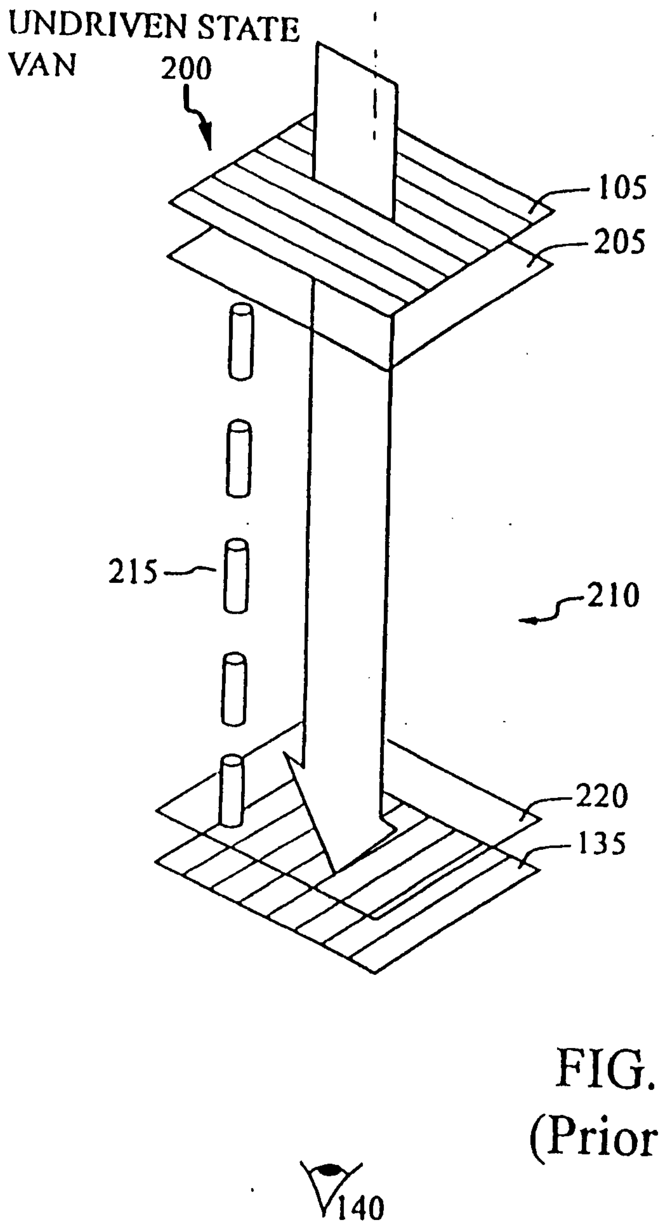

FIG. 2A
(Prior Art)

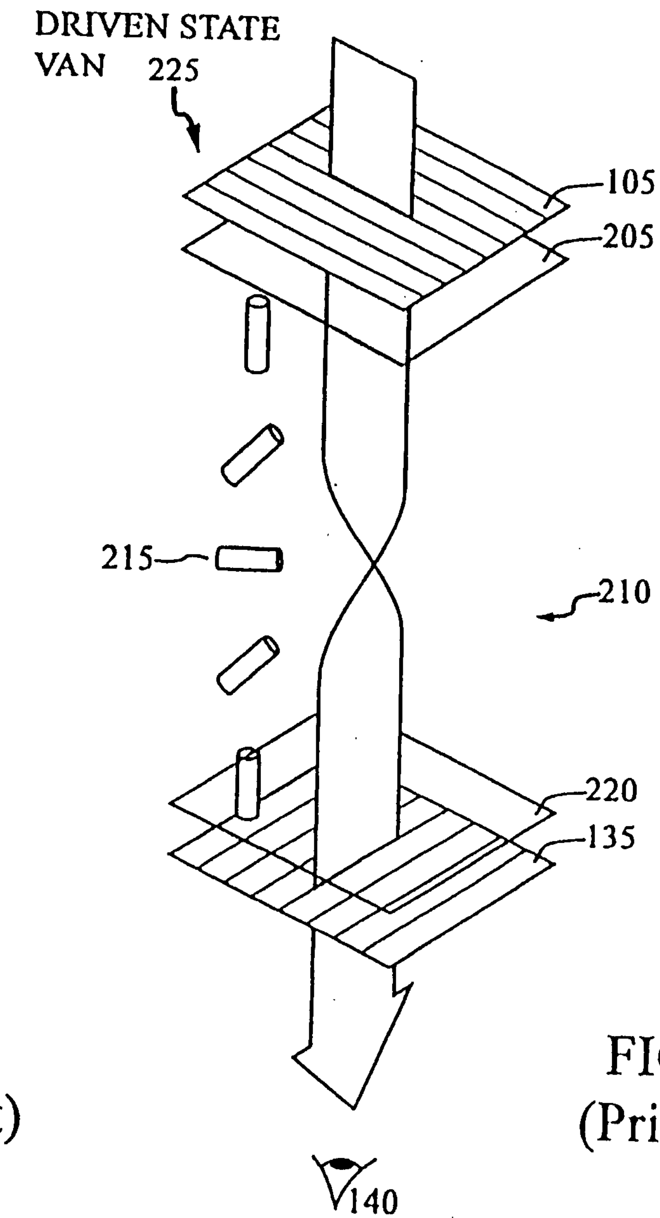

FIG. 2B
(Prior Art)

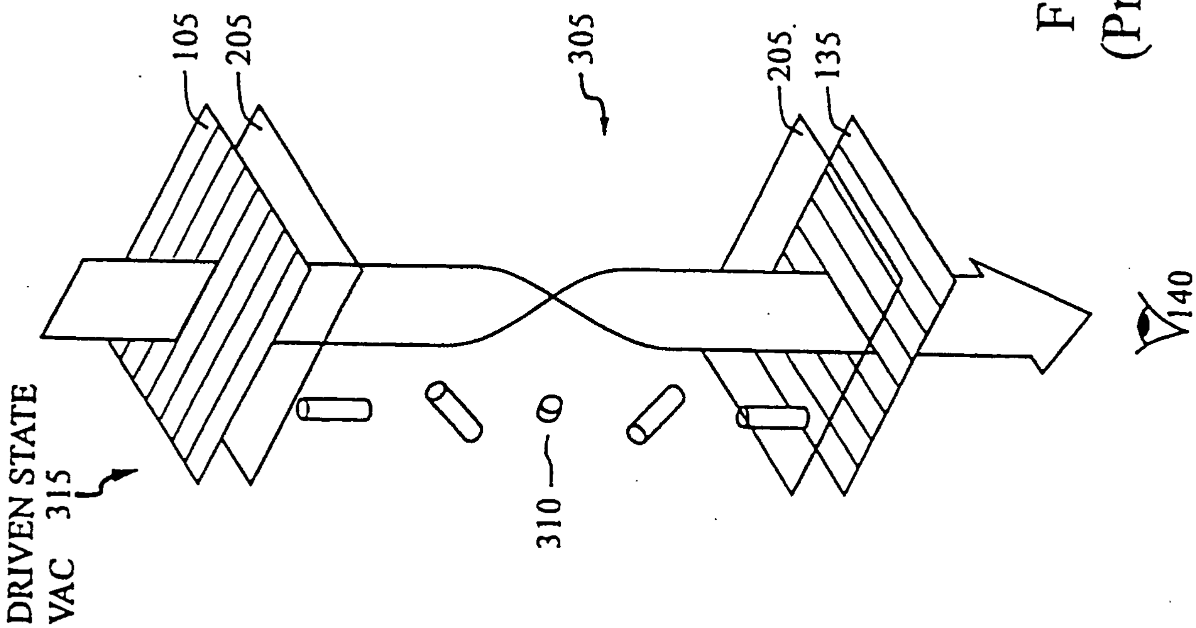

FIG. 3B
(Prior Art)

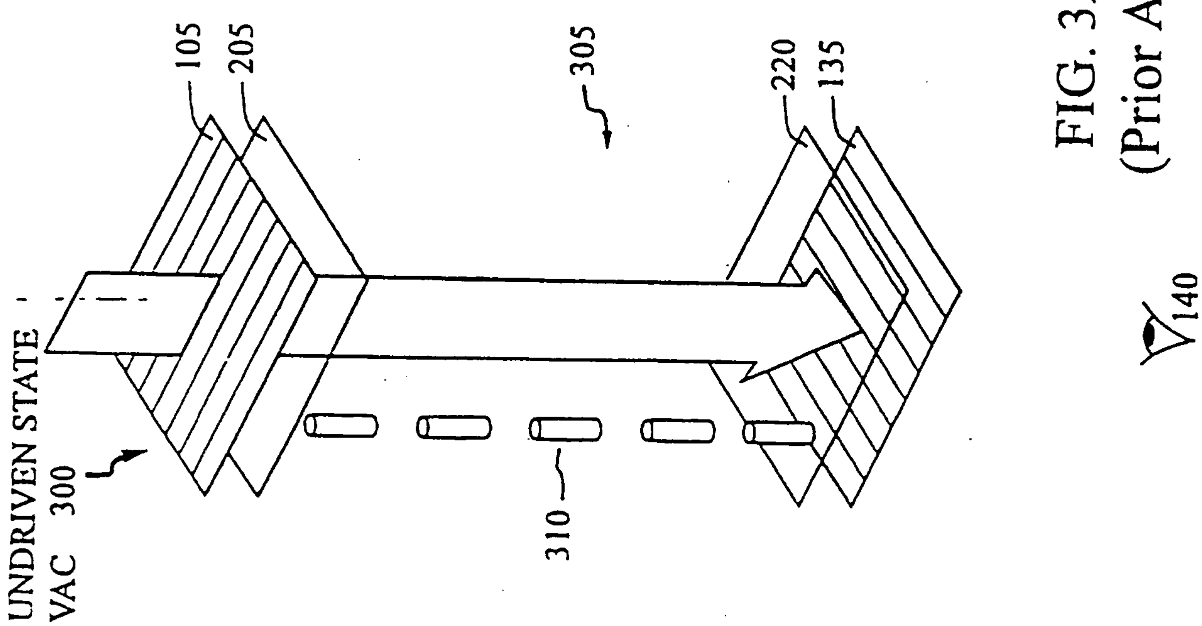

FIG. 3A
(Prior Art)

FIG. 4
(Prior Art)

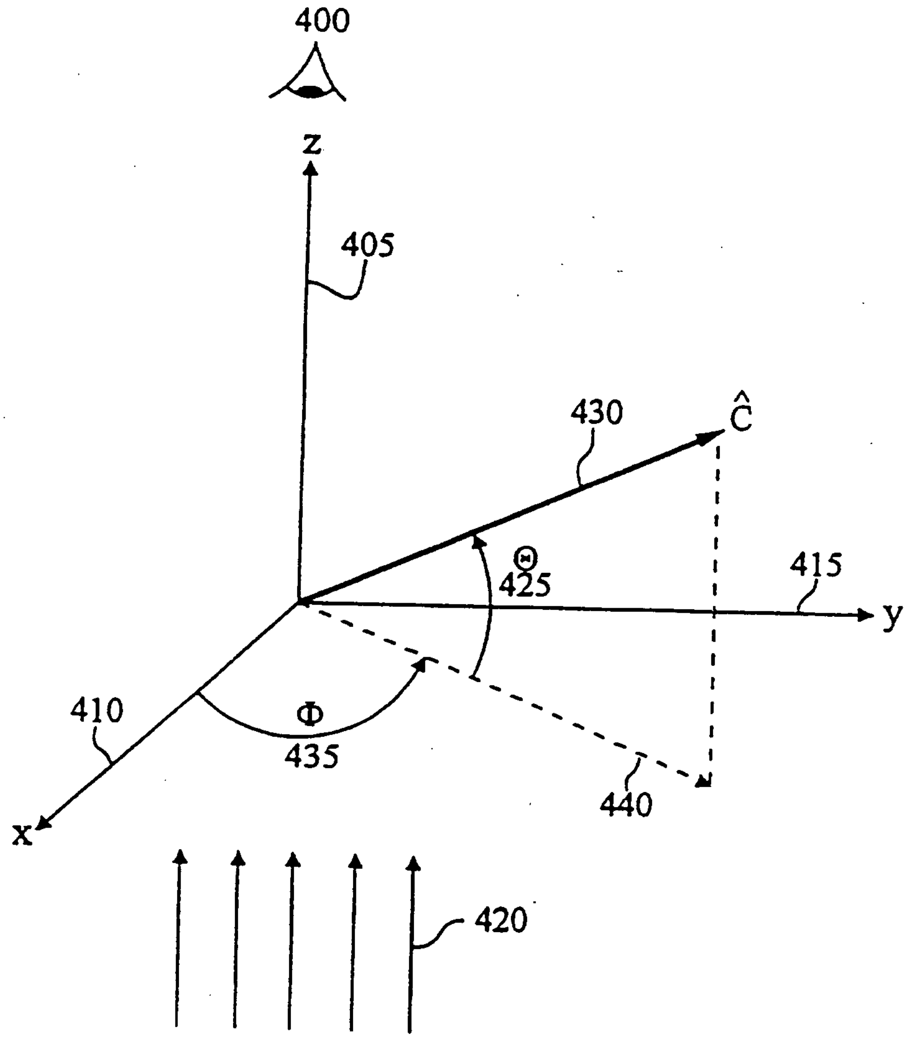

FIG. 5

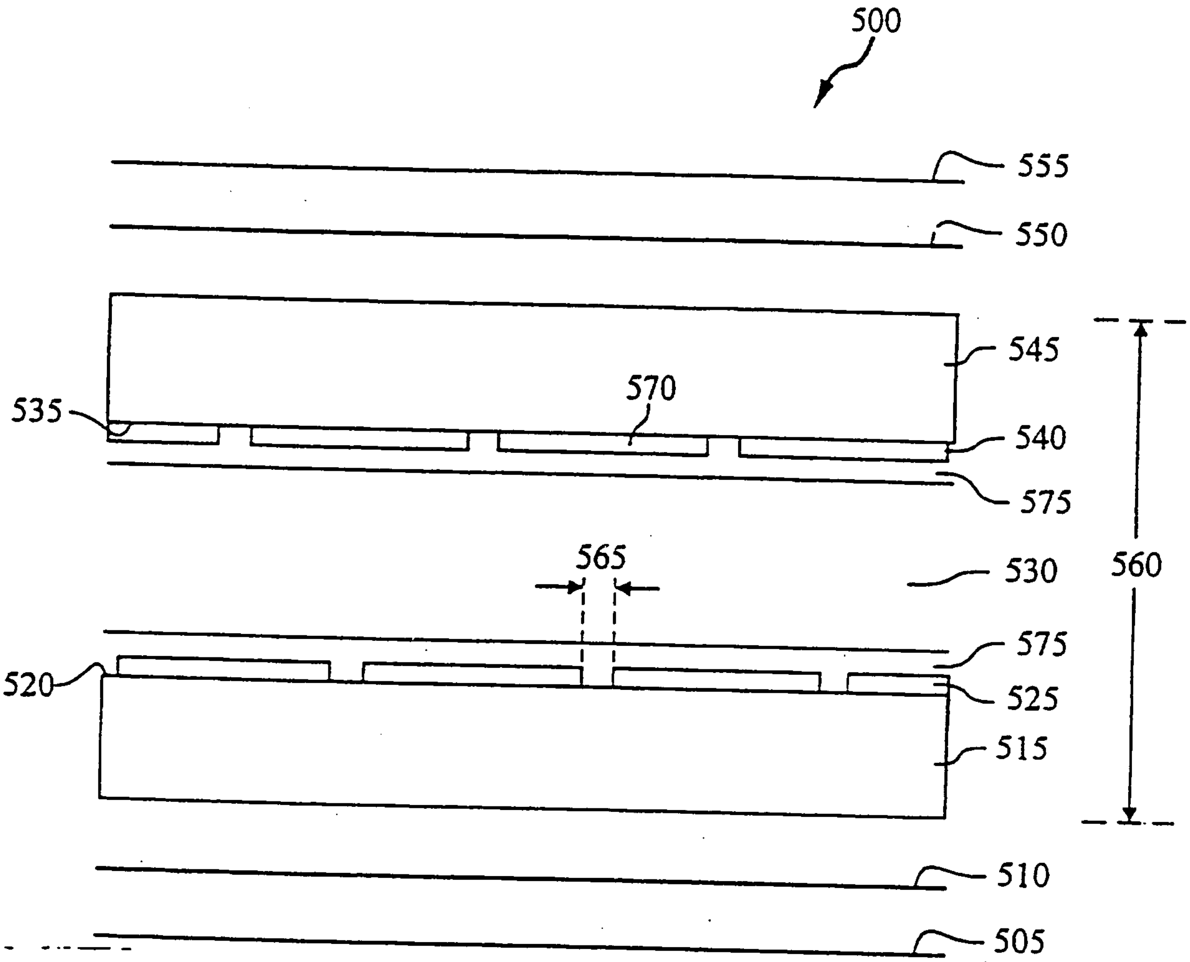
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FIG. 6

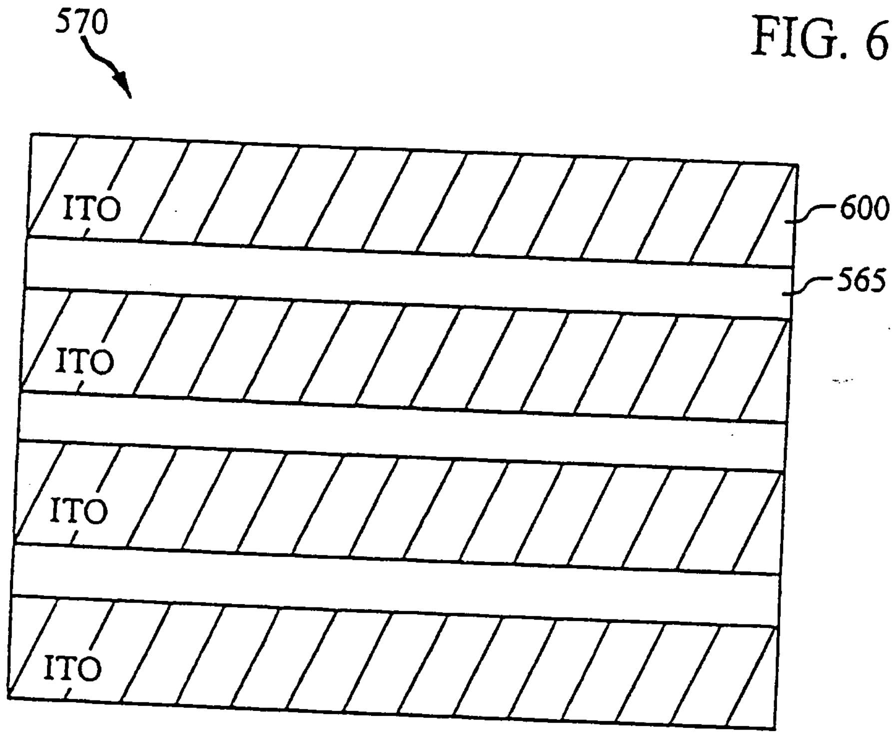

FIG. 7